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ATOMIC OXYGEN BEAM SOURCE FOR EROSION SIMULATION

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ABSTRACT

We describe a device for the production of low energy (3–10 eV) neutral atomic beams for surface modification studies, which reproduces the flux of atomic oxygen in low Earth orbit. The beam is produced by the acceleration of plasma ions onto a negatively biased plate of high-Z metal; the ions are neutralized and reflected by the surface, retaining some fraction of their incident kinetic energy, forming a beam of atoms. The plasma is generated by a coaxial RF exciter which produces a magnetically-confined (4 kG) plasma column. At the end of the column ions fall through the sheath to the plate, whose bias relative to the plasma can be varied to adjust the beam energy. The source provides a neutral flux $\approx 5 \times 10^{16}/\mathrm{cm}^2\mathrm{s}$ at a distance of 9 cm and a fluence $\approx 10^{20}/\mathrm{cm}^2$ in five hours. The composition and energy of inert gas beams has been diagnosed using a mass spectrometer/energy analyzer. The energy spectra of the beams demonstrate energies in the range 5–15 eV, and qualitatively show expected dependences upon incident and reflecting atom species and potential drop. Samples of carbon film, carbon-based paint, Kapton, mylar, and teflon exposed to atomic O beams show erosion quite similar to that observed in orbit on the Space Shuttle.

INTRODUCTION

In low Earth orbit, about 150-300 km altitude, the atmosphere consists primarily of atomic oxygen and molecular nitrogen. The surface of an orbiting spacecraft collides with these species with high relative velocity—the O atoms carry about 5 eV kinetic energy in the spacecraft frame. Spacecraft surfaces are thus exposed to a flux of highly reactive energetic O, ranging from 10^{13} to $10^{16}/\mathrm{cm}^2$ s, depending upon altitude. Observed effects of this bombardment include the production of an optical glow in front of ramming surfaces (the "spacecraft glow" phenomenon[1]) and the erosion of exposed surface materials.

Structures intended to remain in service in low orbit for many years, such as the Space Station, must employ protective surface materials and coatings which can withstand this chemically active flux. Thus there is a need for a source of "superthermal" (4–20 eV) neutral beams to study in the laboratory the effects of the energetic neutral bombardment, and for accelerated testing of candidate materials and coatings, simulating years of on-orbit exposure within a few days.

The need for laboratory facilities for studying the interaction of superthermal (5 eV) atomic oxygen with materials, including its role in the degradation of spacecraft surface materials and in the spacecraft glow phenomenon, has led to the development over the past several years of several new systems using different methods to achieve high fluxes of energetic oxygen atoms.

Besides their application to spacecraft environmental effects, these oxygen beam sources (and low energy neutral beam sources in general) are useful tools for many other purposes. Likely research "spinoffs" for these atomic beam techniques include: beam-surface interactions, atomic scattering, gas phase "hot atom" chemical reactions, and materials processing and surface modification technologies, such as semiconductor etching. Many of these processes have not been well studied at these energies because high flux sources have not been available—older methods of producing neutral beams (such as thermal effusion as in chemical molecular beam experiments,

or acceleration and charge exchange neutralization of ion beams) do not work well in this energy range.

We will describe the operating principles and characterization of a system for the production of high-flux low-energy neutral beams which is based on a coaxial RF plasma source and utilizes a biased metal surface for the acceleration and neutralization of plasma ions. In this paper we emphasize the characterization of the beam energy and tests of the principles on which beam production is based. In an accompanying paper[2] results are presented from experiments to measure the beam flux and from material exposures performed to evaluate the beam's reproduction of effects due to exposure in orbit. The beam facility, developed at Princeton under contract for Marshall Space Flight Center, has proven successful in meeting the requirements for simulating the orbital interaction of atomic oxygen with materials, and shows promise for other technological applications. The beam source is capable of sustained production of high flux beams of essentially 100% atomic O.

PRINCIPLES OF OPERATION

The method we have used for producing a low energy neutral beam utilizes a metal surface in contact with a magnetically confined plasma to accelerate and neutralize plasma ions. The metal plate is biased negative with respect to the plasma potential, and plasma ions are accelerated onto the surface, attaining an energy determined by the bias voltage. The ions are neutralized by picking up an electron from the negatively charged metal, and undergo collisions with the atoms of the solid surface. If the metal atoms are much more massive than the ions, the incident particles are mostly reflected back from the surface, retaining a large fraction of their incident kinetic energy, thus forming a beam of superthermal neutrals of adjustable energy.

The interaction of the plasma ions with the metal surface is itself a process of fundamental interest. These interactions are not well studied experimentally in the energy range below 100 eV, due to lack of sources and diagnostics. Such processes are important in various technological areas, for example, in the edge regions of fusion plasma devices where the plasma interacts with material surfaces. The characteristics of the reflected neutrals produced in our beam source can yield significant new experimental data on these interactions and provide a test of theoretical models used to describe them. Calculations have been made with TRIM (TRansport of Ions in Matter), a Monte Carlo code used to model the interaction of a particle with a solid surface[3,4], in order to predict the reflection efficiency and energy spectrum for various incident ions and surfaces. The TRIM code follows the trajectory of each incident particle, calculating the effect of each successive collision with the atoms of the solid, and also models the effect of energy loss to electrons and of surface binding forces on the incident particle. The surface binding forces are modeled as a planar attractive potential directed toward the surface, which can only approximate the complex interaction with the atoms of the surface; thus the model's predictions are less certain for species which may tend to bind strongly (e.g. oxygen) than for those which interact more weakly (noble gases).

The reflection efficiency and energy spectrum of the reflected beam depend upon the exact species of the incident particles and surface atoms, their relative masses and the strength of binding forces acting between them, and upon the condition of the surface with respect to roughness and impurities. In general the TRIM calculations predict that for a large enough mass ratio, low energy (5-100 eV) ions are reflected fairly efficiently as neutral atoms, with the energy spectra peaked around a particular fraction of the incident energy, having a characteristic spread of a few eV. The larger the mass ratio between incident and surface atoms, the larger is the fraction of incident energy at which the peak in the reflected spectrum occurs. The expected angular distribution of the reflected beam is roughly a cosine distribution about the normal to the surface. Figure 1 shows an example of the energy spectrum of the reflected neutrals as predicted by the TRIM code for oxygen incident on molybdenum (a reflecting surface frequently used in our erosion experiments). Note that the spectrum is fairly peaked at around 6 eV, with a spread of a few eV.

Figure 2 shows the predicted reflection efficiency for oxygen atoms incident on molybdenum over the energy range 10–50 eV. Also shown is the fraction of the incident energy at which the peak of the reflected energy spectrum occurs for particles reflected into the solid angle range from 25–45° from the surface normal (±10° from our usual experimental viewing angle). Over a wide range of incident energies the reflection efficiency is around 60% and the ratio of the reflected energy peak to the incident energy is 0.40–0.50. For example, at 30 eV incident energy $E_{ref}/E_{inc} = 0.46$; this value from TRIM calculations can be compared with the energy retained upon a reflection due to a single elastic collision at 35° from the incident path, which for these masses would be

$$E_{ref}/E_{inc} = [m_1^2 + m_2^2 + 2m_1m_2cos\theta_{CM}]/(m_1 + m_2)^2 = 0.54$$

SYSTEM DESIGN AND OPERATION

Figure 3 shows a cross-sectional view of our low energy neutral beam apparatus. It has two basic parts: a plasma chamber containing a coaxial plasma source and the neutralizing plate, and an experimental 'target'

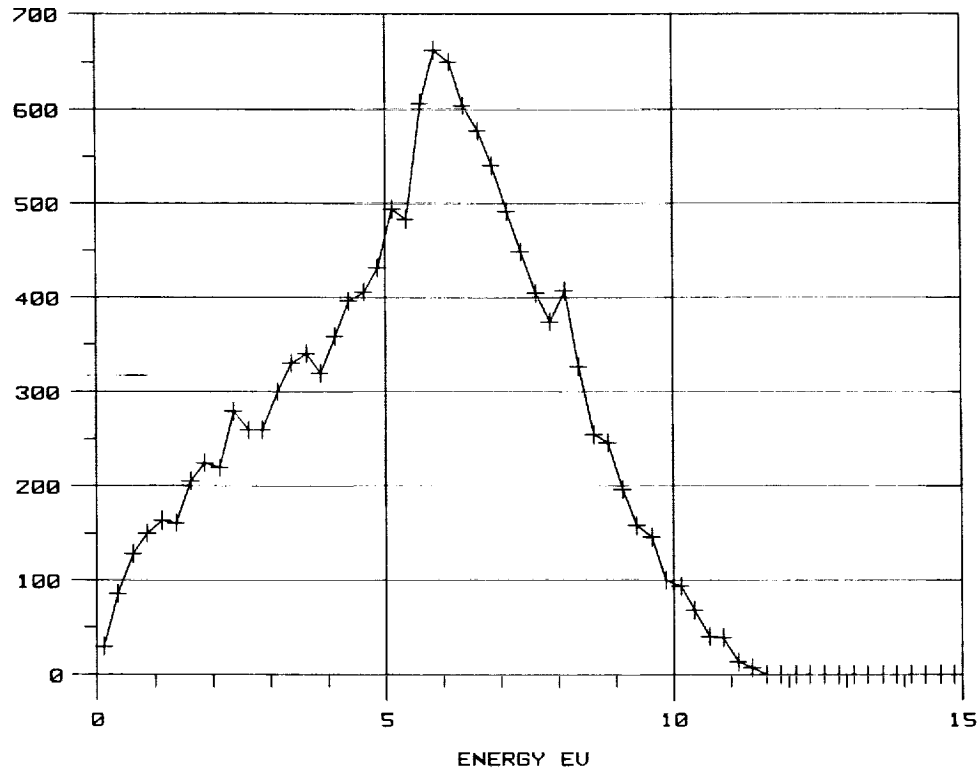

Figure 1: TRIM calculations for the reflected energy spectrum of oxygen atoms reflected from a molybdenum surface for an incident energy of 15 eV, for all reflection angles (0–90° from normal). The calculation used an attractive potential of 2 eV to model the binding forces between the oxygen and surface molybdenum atoms.

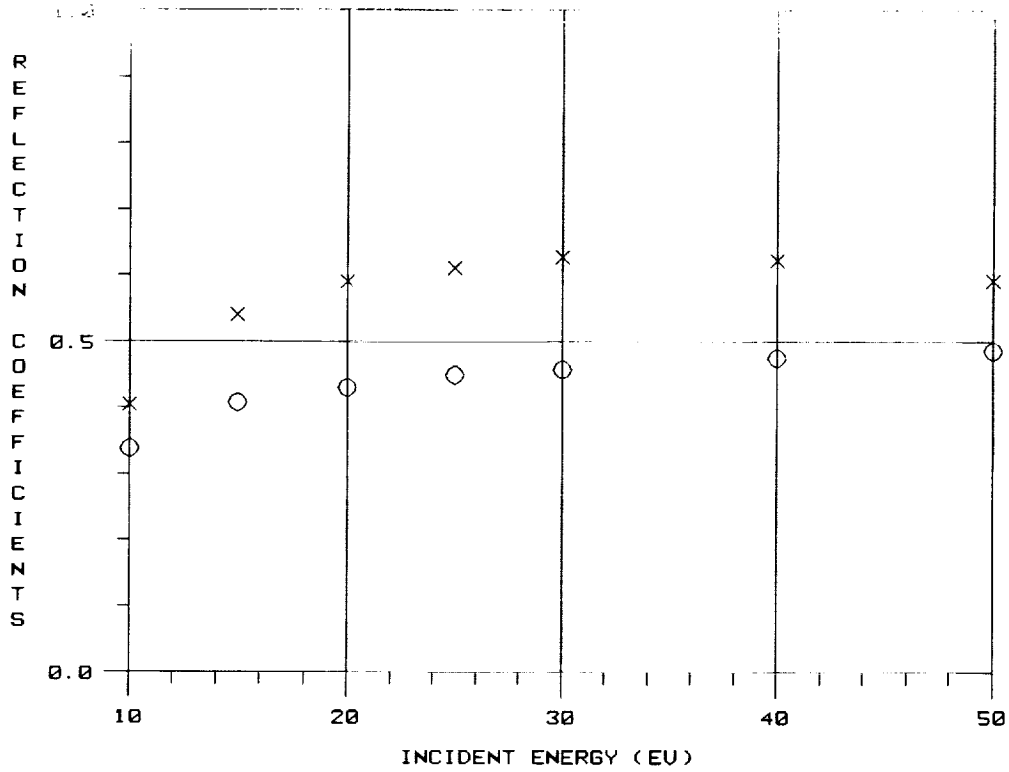

Figure 2: TRIM predictions for the reflection of oxygen ions from molybdenum with 10–50 eV incident energy. Crosses show the reflection efficiency; circles show the energy at which the peak of the reflected energy spectrum occurs for reflection angles $35 \pm 10°$ as a fraction of the incident energy.

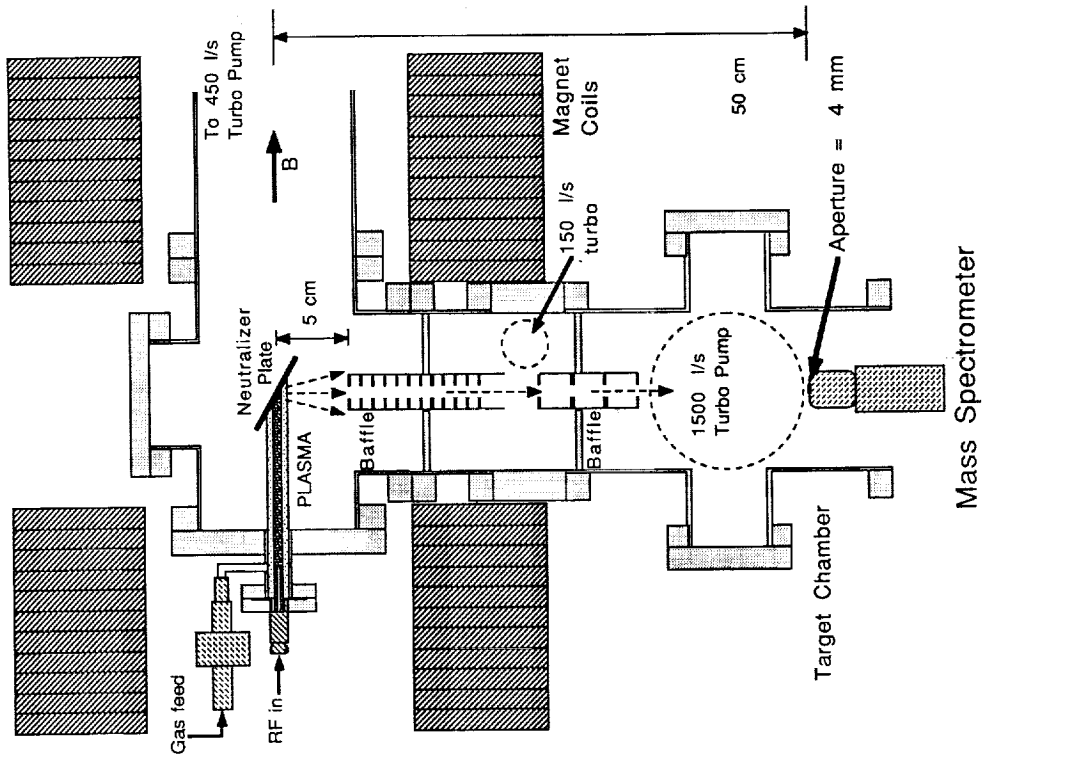

Figure 3: Cross-section view of the Princeton Low Energy Neutral Beam facility, as configured for beam energy measurements.

chamber oriented perpendicularly.

In order to produce pure oxygen plasmas, we use an RF driven plasma source, thus avoiding the problems associated with hot filaments and cathodes that limit the oxygen content of simple arc and glow discharges. Our system is based on a magnetically confined coaxial plasma source of the type developed by Motley and co-workers[5]. The source is driven by 1 kW microwave power at 2.45 GHz applied to a center conductor coaxial with an Inconel outer cylinder, which acts as a quarter-wave antenna. The RF propagates through the plasma as lower hybrid waves. The plasma source produces an intense plasma column of about 1 cm radius. The Inconel outer conductor and the back side of the ceramic seal are water cooled.

The magnetic field in the plasma source is produced by two sets of 11 water-cooled coils arranged in a Helmholtz-like configuration. A current of 440 A is passed through the coils, yielding an axial field of 4 kG.

Plasma particles travel along the field lines from the coaxial source to the neutralizer in a well-confined cylindrical column. The neutralizing surface is provided by a thin plate of metal mounted on a copper block which can be water- or air-cooled and which can also be heated to a few hundred degrees C by means of an internal heating element for purposes of outgassing. The surface materials used most often have been molybdenum and tantalum, chosen for their high atomic mass, resistance to reaction with oxygen, and low sputtering (platinum and gold surfaces have also been used).

The plate can be rotated to any angle with respect to the B field, and is usually oriented at about 55°. Because the potential drop across the sheath to the plate is large compared to the ion thermal kinetic energy, the ions impinge on the surface at nearly normal incidence. The reflected neutral beam is directed across the magnetic field, and thus the field keeps charged particles away from the beam target area. Because the plasma column striking the neutralizer is small in radial extent the neutral source is well defined and tightly focused. The neutralizer can be biased from -50 to +15 V relative to ground (positive bias limited by the electron current drawn); combined with the positive plasma space potential this gives incident ion energies from about 10 to 60 eV. The ion current to the neutralizer plate is measured from the voltage drop across a 1 Ω resistance in the power supply circuit using an oscilloscope.

Both parts of the vacuum vessel are composed of 6 inch diameter cylindrical stainless steel sections. Two baffled gas chokes may be installed in the target chamber, creating two stages of differential pumping. The high vacuum stage is connected to a 1500 l/s turbo pump. During beam production, operating pressure is a few mTorr in the plasma chamber, but can be held to a few times 10^{-7} Torr in the experimental chamber with the differential pumping. To reduce the danger of pumping pure oxygen, we bleed nitrogen into the backing pump at a nitrogen/oxygen ratio about 2:1.

For measurement of the properties of the plasma the system is equipped with two electrostatic probes, one a single Langmuir probe and the other an electron emitting hot probe. Each probe can be independently moved radially and axially through nearly the entire length of the plasma column; the probes have been used to measure the plasma density and electron temperature and the plasma space potential. The hot probe is especially useful for directly measuring the plasma potential, but has a limited range of densities over which it can operate. A monochromator spectrograph has also been used to measure the plasma emission spectrum, viewing the plasma column through a quartz window in the plasma chamber (not shown). Plasma emission spectra show virtually complete dissociation in oxygen plasma: the ions are O^+ rather than O_2^+. This is crucial since we desire a beam of atomic O.

The system can achieve a sustained ion current to the plate of 4 A in O^+ or Ar^+. Using the predicted reflection efficiency for O reflected from Mo this gives:

$$\text{O flux} > 5 \times 10^{16} cm^{-2} s^{-1}$$

at the usual target position about 9 cm from the neutralizer.

The system is operated in a pulsed mode, with pulse lengths of a few msec. Duty cycles of up to 10% have been achieved sustainably, limited by heating of the coaxial exciter center conductor. The system operates reliably in 100% oxygen plasmas over the long run times (several hours) needed to achieve high fluence ($10^{20} cm^{-2}$) exposures.

The damaging effects of atomic oxygen on system components have been small. The stainless steel center conductor of the coaxial is corroded visibly, but is robust enough to survive more than 100 hours plasma operation; no limit to survival time has been reached for any other system component.

NEUTRAL BEAM MEASUREMENTS

Measurements of the absolute neutral atom flux for atomic oxygen beams have been made in collaboration with the Physical Science Branch of the Materials Laboratory at Marshall Space Flight Center and are reported in a separate paper in these proceedings [2]. These measurements were made using catalytic probes [6] which measure the heat produced by the recombination of oxygen atoms striking a catalytic silver oxide surface. These measurements support the predicted flux levels to within the experimental error (about a factor of two). The measurements also confirm the expected variation of the flux as the inverse square of the distance from the neutralizer. Measurements of the angular distribution of the beam flux from the relative erosion rates of polyethylene targets exposed simultaneously in the target chamber are also reported in Vaughn et al.

In this paper we report the results of direct measurements of neutral beam energy spectra which have been made using an energy analyzing quadrupole mass spectrometer (VG model SXP-500) installed as in Fig. 3. Neutral particles enter this instrument through a 4 mm aperture and pass through an "ion source" region where a small fraction of them are ionized by electron impact. The ions then pass into a cylindrical mirror analyzer (CMA), which uses electrostatic focusing to allow only ions with a certain desired energy to pass through. The energy spectrum of incoming particles is obtained by scanning the energy at which ions can pass through the CMA. Ions then enter an electric quadrupole mass filter which will allow only ions of a particular q/m ratio to pass through. These ions are then detected by a channeltron electron multiplier.

The likelihood of an incoming particle's detection is determined by the probability of ionization upon passing through the ionizing region; this is proportional to the time spent in the region, and thus inversely proportional to the velocity. Therefore, the signal due to the thermal neutral gas (background from the gas feed to the plasma source) is much larger than the signal from the superthermal neutral beam (detected at 50 cm from the neutralizer), even with the background pressure in the spectrometer chamber kept quite low by differential pumping. Because of this effect and the instrumental broadening of the thermal gas energy spectrum, the tail of the apparent thermal distribution obscures the low energy end of the spectrum of the reflected beam. This imposes a low energy limit to observation of the spectrum of 2–3 eV.

Argon rather than oxygen atom beams have been used to perform most of the energy spectrum measurements for the source, for three reasons. First, argon has a high cross-section for electron-impact ionization. Second, being more massive than oxygen, argon has a lower velocity at a given energy, thus a longer residence time in the ionizing region of the spectrometer. These two effects make the quadrupole much more sensitive to argon than to oxygen. In addition, for molecular gases, dissociation of thermal background molecules in the ionizer creates atoms with a few eV energy (Franck-Condon dissociation energy). The signal from these energetic atoms can

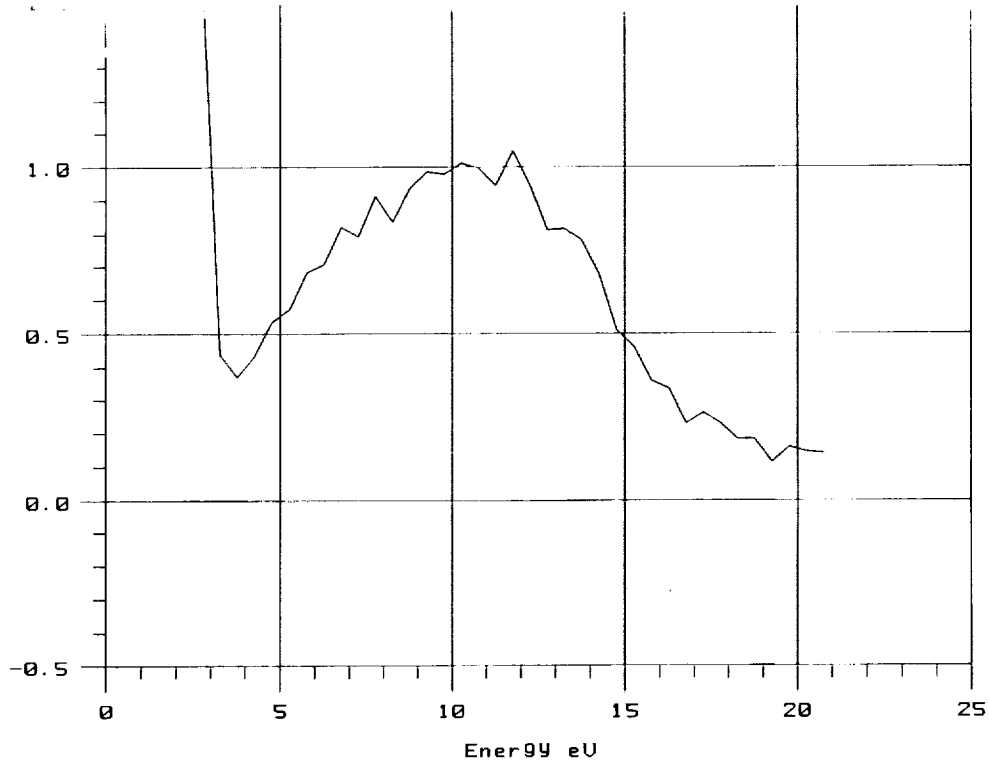

Figure 4: Energy spectrum for argon beam reflected from tantalum as measured using CMA energy analyzer. Instrumentally broadened signal from backgroung thermal gas obscures low energy end of beam spectrum. Data shown averaged to same energy resolution as numerical prediction (Figure 5).

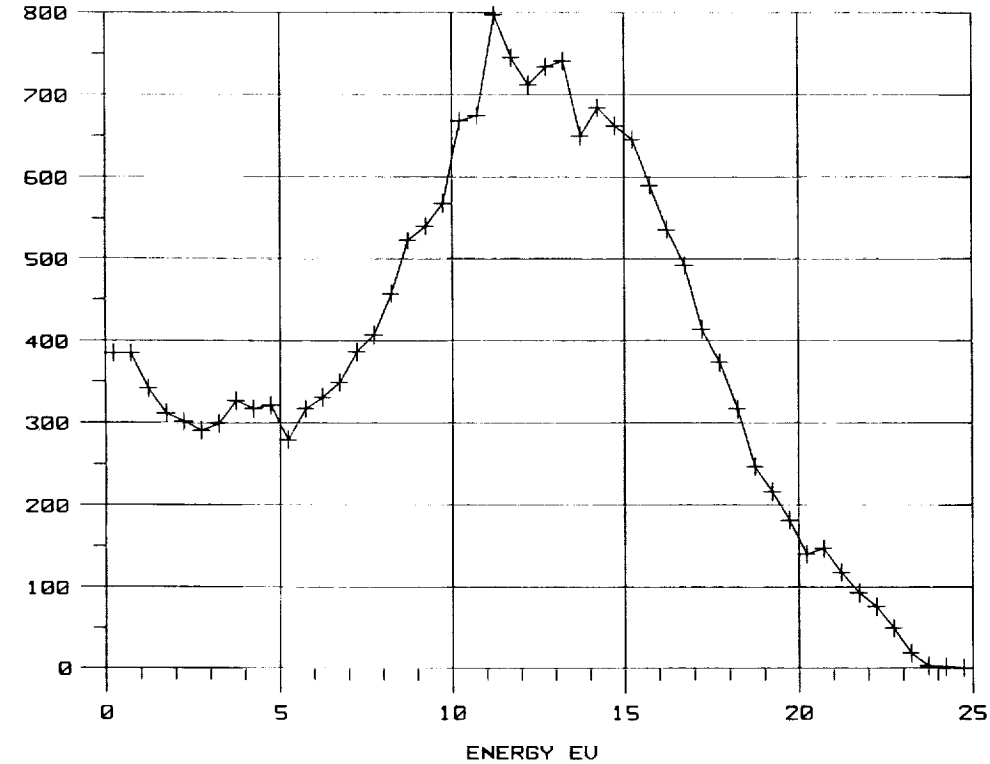

Figure 5: TRIM calculations for the reflected energy spectrum of argon atoms reflected from a tantalum surface for an incident energy of 30 eV, for all angles of reflection.

swamp the signal from the much less efficiently ionized superthermal neutral beam atoms in the affected energy range.

Figure 4 shows an example of the energy spectrum for an argon beam reflected from a clean (outgassed) tantalum surface. The peak energy is 10-12 eV with a spread (HWHM) of 4-5 eV. This spectrum can be compared with TRIM code results (Figure 5), which show a quite similar peak energy and energy spread. Energy spectra with characteristics like those of Fig. 4 are obtained during the first several minutes of beam production, after which the peak energy begins to shift downward, falling to about 7 eV for Ar on Ta after about 30-40 minutes of beam production. We believe the time variaton is caused by gas loading of the reflecting surface, as discussed below.

Evidence for the effect of the plate bias (i.e. accelerating potential across the sheath) on the energy is shown in Figure 6 for argon incident on molybdenum. A change in the sheath potential, measured with a Langmuir probe, from 40 to 10 Volts shifts the peak from about 8 to 5 eV, demonstrating the ability to control the energy of the beam.

In experiments performed with other plasma species and reflecting materials, we have seen qualitatively the expected variation in the beam energies depending upon the atomic masses of the incident and surface species, at least for those species for which we have collected significant data (for some cases examined, the data were not clear enough to characterize the spectrum). For example, the reflected energy spectrum for argon incident on molybdenum occurs at lower energies than for Ar incident on tantalum at comparable incident ion energy, demonstrating the dependence on target mass. Also, the reflected energy spectrum of Krypton incident on Ta falls at lower energies than that for Ar on Ta at comparable energy, demonstrating the expected dependence on incident ion mass

However, as mentioned above a complication arises from the contamination of the surface by atoms of the plasma species. TRIM predicts that at sufficient impact energies some incident particles will be implanted in the surface material rather than reflected; the residence time for such implanted particles in the metal is unknown. In addition, surface adsorption may also occur, especially for chemically reactive species. Incident particles which collide with implanted or adsorbed atoms of the same mass will lose more of their kinetic energy than if colliding

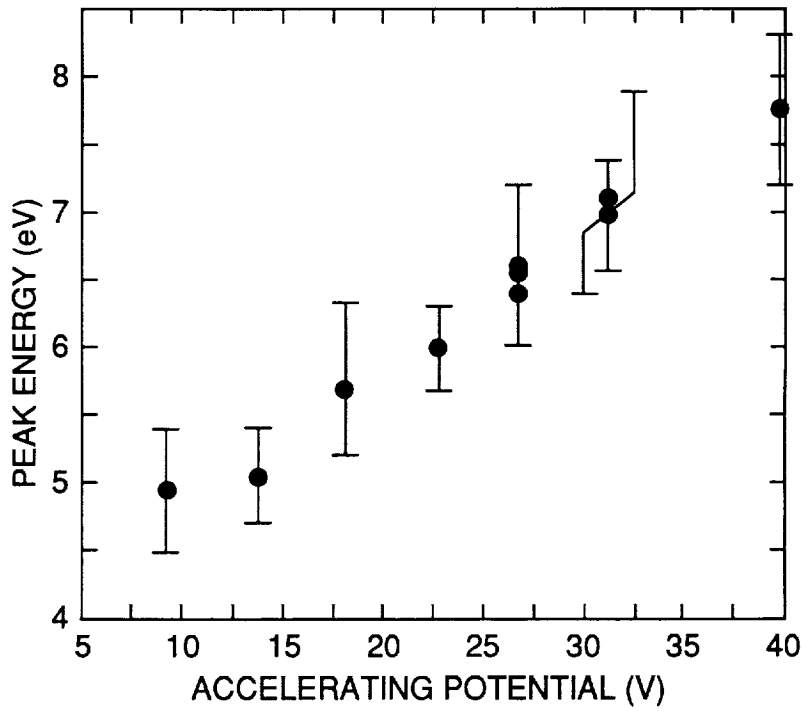

Figure 6: Location of the peak in the energy spectrum for argon beams reflected from a molybdenum surface, as a function of the incident energy of the ions (determined by the potential drop across the sheath to the reflecting surface). Error bars indicate the approximate uncertainty determining the peak from the mass spectrometer data; since the peaks are relatively broad and flat, determining the exact position of the maximum is somewhat uncertain.

only with the heavy metal atoms; this will result in a reflected beam of lower energy neutrals. Beginning with an outgassed reflecting surface, it has been observed that the energy spectrum of the neutral beam shifts to lower energies over the course of several minutes of operation. The spectrum can be shifted back to higher energies by outgassing the neutralizing surface. Thus the reflected energy spectrum from the interaction of an ion species with a homogeneous metal surface will be different from the spectrum seen in practical, prolonged steady beam production.

The unknown degree of occupation of the surface material by oxygen atoms makes it difficult to predict from theory exactly what the beam energy spectrum will be for long-time oxygen beam exposures. Direct measurements of the oxygen beam energy spectrum during steady-state beam production are necessary, and this is now one of the principal issues that need to be resolved.

CONCLUSIONS AND FUTURE WORK

The neutral beam source described here produces atomic beams with energy spectra that have been directly measured (for inert gas beams) to be in the desired energy range (about 4-15 eV), with an adjustable peak energy and a spectrum width of a few eV. Some qualitative features of the reflection of low energy inert gas atoms from surfaces have been observed from the measurements to date, and are in rough agreement with the numerical simulations from theory. It is clear, however, from the behavior over time of the observed spectra that surface loading of the reflecting material by the working gas ions plays a large role in the reflection physics. To explore this further we have added heating coils to the mounting of the neutralizing plate so that we can either heat cycle the plate between spectral measurements, or raise the plate to such a temperature that the gas atoms are expelled at the same rate they arrive so that suface conditions are stable.

Additionally, we intend to increase the duty cycle of the source above 10% by actively cooling the center conductor, and to reduce the O_2 pressure in the spectrometer chamber to permit the measurement of atomic oxygen beam spectra. The presence of O beams at high flux levels has already been conclusively demonstrated by other measurements (including direct flux measurements with catalytic probes, and erosion of exposed materials[2]), and the beam source has proven a useful simulation of the atomic oxygen bombardment in orbit, but the energy spectrum remains to be determined.

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